Binary Quasar Candidates:
IFU Spectroscopy with VIMOS/VLT

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Quasars (QSOs)

- Active galactic nuclei (AGN)
- Accretion onto supermassive black hole

Quasars

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- Accretion onto supermassive black hole

Binary quasars

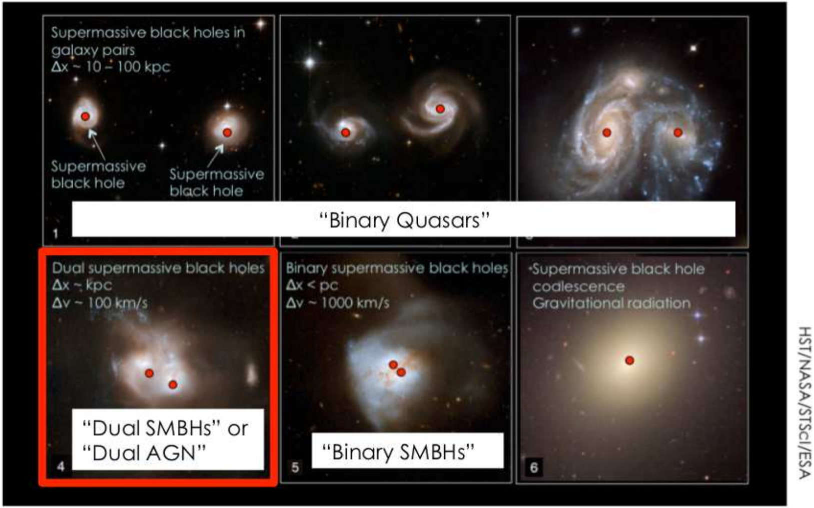
Should be frequent, if:

- Galaxies evolve through mergers
- QSOs triggered by mergers

. . . Directly observed: ~ 5

Galaxy pairs, Black-hole pairs

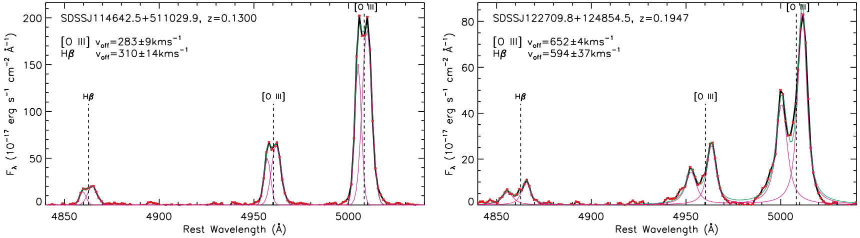
Different separations



Spectroscopic Binary Quasar Candidates

SDSS catalogue

Double-peaked [O III] lines in SDSS (Liu et al. 2010)

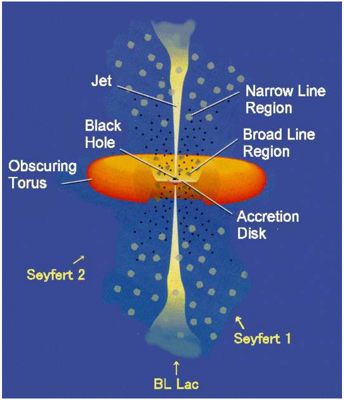


Double-peaked lines from binary quasars? Or outflows?

Origin of emission lines

Narrow-Line Region (NLR)

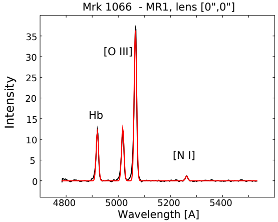
Unified Model of AGN



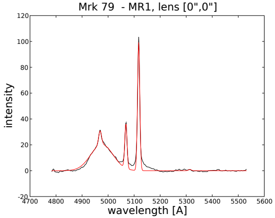
Urry & Padovani (1995)

NLRs: Gas ionised by AGN

$$T \sim 10^4\,\mathrm{K},\ n_\mathrm{e} \sim 10^2\,\mathrm{cm}^{-3}$$



AGN type 2



AGN type 1

VIMOS/VLT spectroscopic follow-up

Stoklasová (Orlitová, PI), Jungwiert, Skalická, Bartošková, Ebrová, Jílková, Křížek

Targets:

- Selected 5 low-z SDSS targets from Liu et al. (2010)
- Selection by redshift ($0.03 < z < 0.07$), luminosity and RA

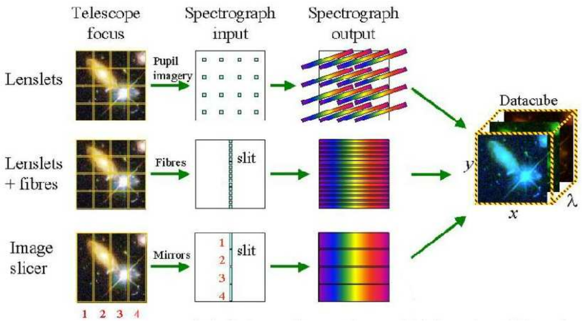
Goals:

- Observe selected candidates with VIMOS
- Derive spatial kinematics and [O III]/Hβ ratio
- Interpret
  - binary AGN?
  - rotation, outflow?
  - projection of two galaxies along LOS?

Integral-Field Spectroscopy (IFU)

1 spectrum is more than 1000 images. 1000 spectra is more than 1 spectrum...

- Spatially resolved spectroscopy
- Simultaneous acquisition of $10^2 - 10^4$ spectra
- Datacube $(x, y, \lambda) \rightarrow$ "3D" spectroscopy



Principles of different integral-field units (IFUs). Credit: University of Durham.

VIMOS/VLT observations

- Targets:
  - SDSS J144804.17+182537.8 $\rightarrow$ Q1418
  - SDSS J151659.24+051751.5 $\rightarrow$ Q1505
  - SDSS J155619.29+094855.5 $\rightarrow$ Q1509
  - SDSS J163056.75+164957.1 $\rightarrow$ Q1616
  - SDSS J230442.82–093345.2 $\rightarrow$ Q23–09
- High-resolution spatial sampling 0.33"/pixel
- Seeing 0.6" – 0.8" (i. e. resolution $\sim$ 0.5 – 1 kpc)
- FOV: 13" $\times$ 13"
- Spectral resolution (R = 2550 $\rightarrow$ 120 km/s)
- Spectral range 4000 – 6000 Å $\rightarrow$ [O III]4959,5007, Hβ em. lines
- Integration 8 $\times$ 1000 s for each target
- We have approx. 300 resultant emission spectra per target

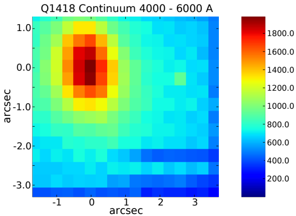
VIMOS – Stellar continuum

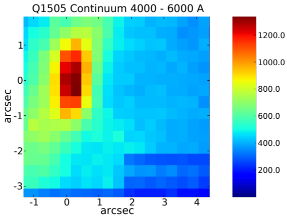
Central 2 – 3 kpc

Q1418

$z = 0.0378$

1" = 0.75 kpc





Q1505

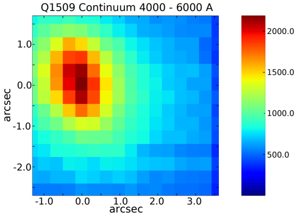
$z = 0.0512$

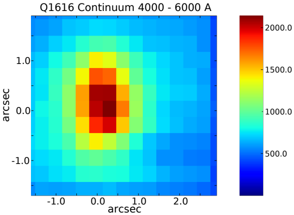
1" = 1 kpc

Q1509

$z = 0.0678$

1" = 1.3 kpc





Q1616

$z = 0.0341$

1" = 0.67 kpc

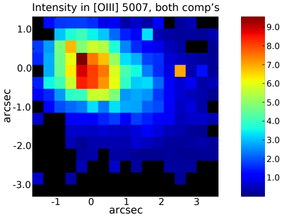
VIMOS – [O III] Emission maps

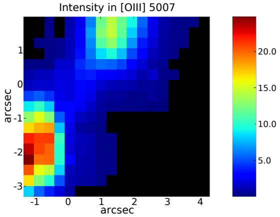
Aligned with continuum, extent: $\sim 1.5 - 3$ kpc

Q1418

$z = 0.0378$

1" = 0.75 kpc





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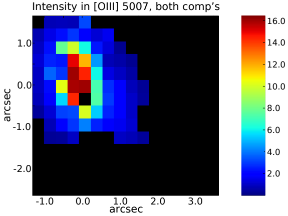
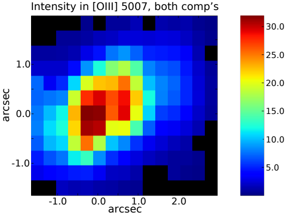




Q1616

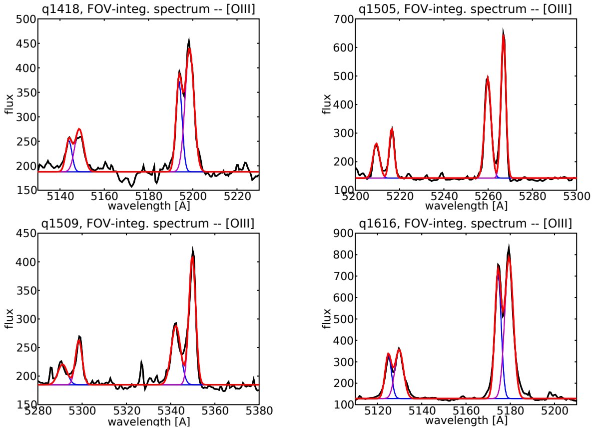
$z = 0.0341$

1" = 0.67 kpc

VIMOS – [O III] spectra integrated over FOV

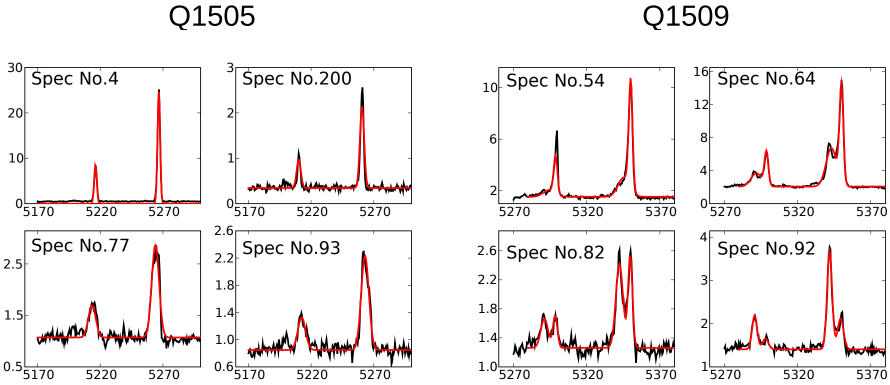
Diagnostics following Blecha et al. (2012) and Smith et al. (2011)

- Peak separation [km/s]: 270, 400, 400, 300
- Centroid offset from $v_{\rm sys}$ [km/s]: 8, 1, 18, 46 ($\to$ no BH influence?)
- Ratios of peak fluxes: 0.7, 0.7, 0.7, 0.9 ($\to$ no BH influence?)



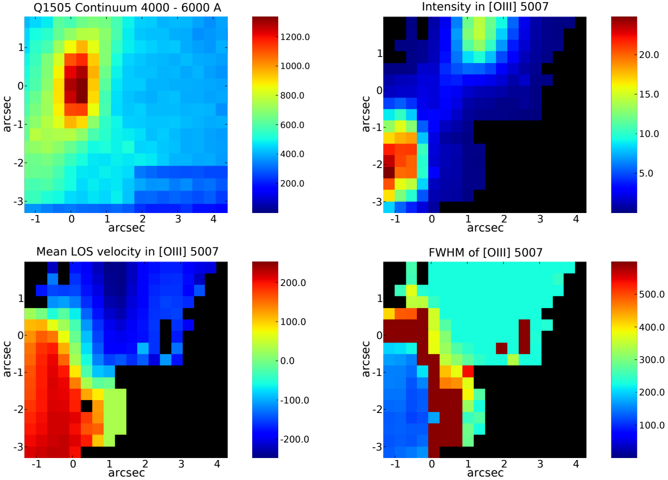
VIMOS - [O III] spectra spatially resolved

- Spectral line profiles: from simple narrow to complex



VIMOS – Q1505

J151659+051752, z = 0.0512, 1" = 3 pixels = 1 kpc

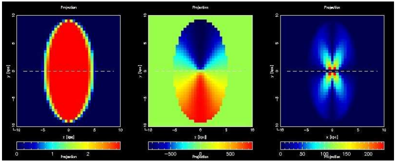


Theoretical I, v, σ maps

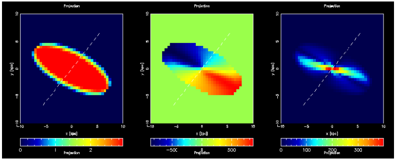
Code by Jugwiert et al. (2007)

- Velocity maxima off-axis:
  in elliptical rotation, or circular rotation + outflow

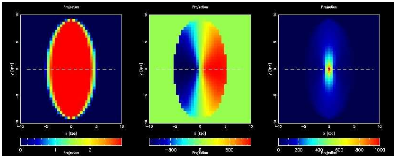
Rotating disk – flat v_r



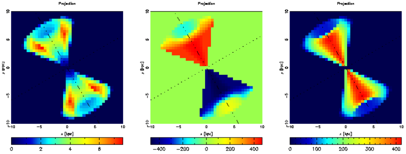
Elliptical rotation



Expanding disk



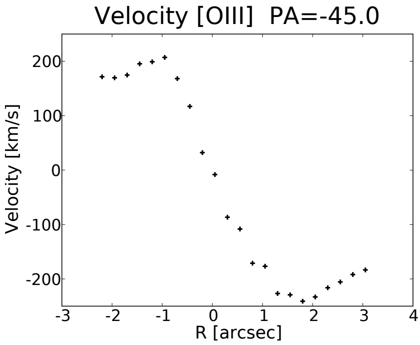
Outflow in a cone

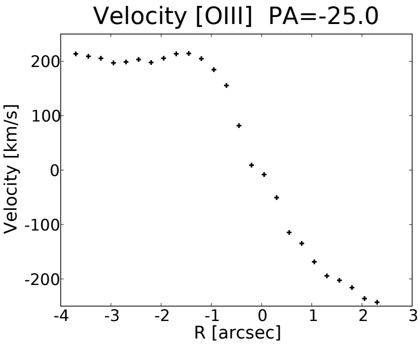


VIMOS – Q1505

1D velocity profiles along "slits"

- Radial profiles indicate rotation

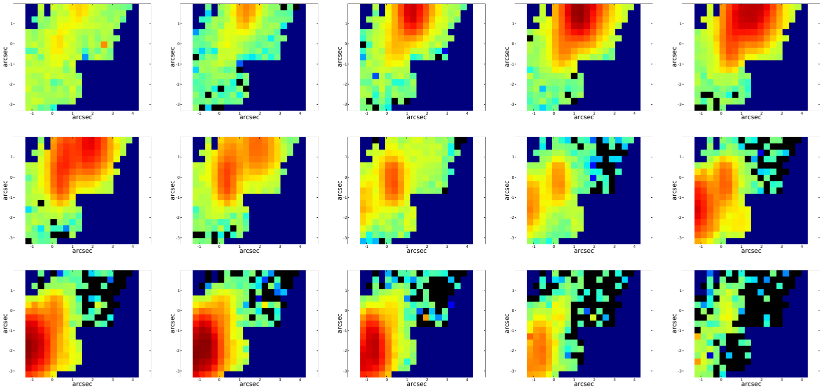




VIMOS – Q1505

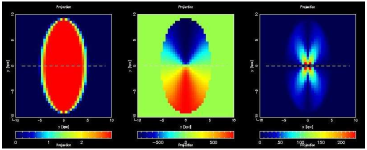
Velocity channel maps for [O III] 5007

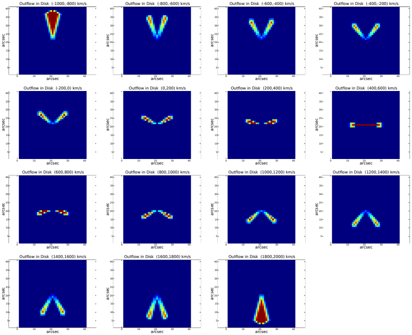
- Range: (–440,420) km/s
- 1 channel: 60 km/s



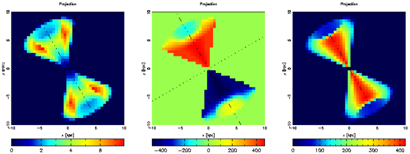
Theoretical velocity channel maps

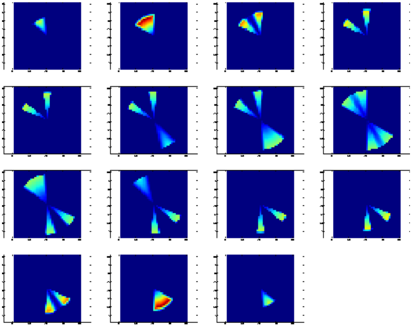
Rotating disk – flat v_r





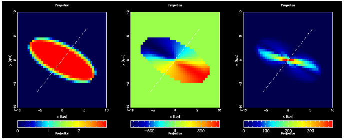
Outflow in a hollow cone

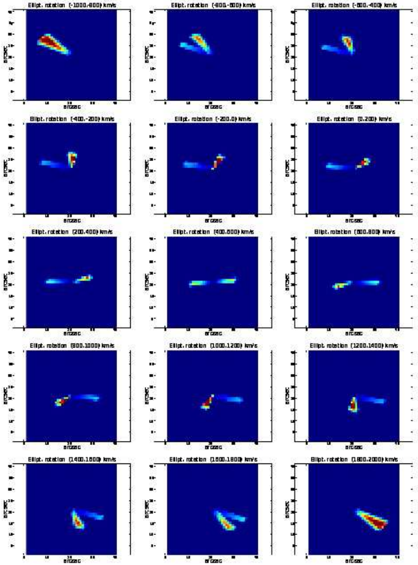




Theoretical velocity channel maps

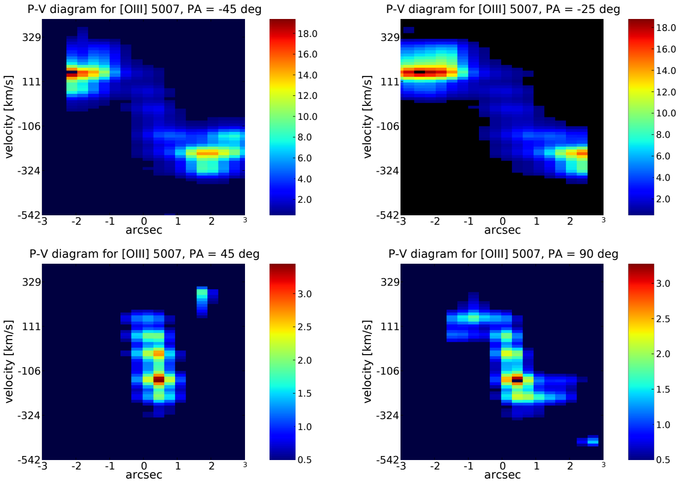
Elliptical rotating disk





VIMOS – Q1505

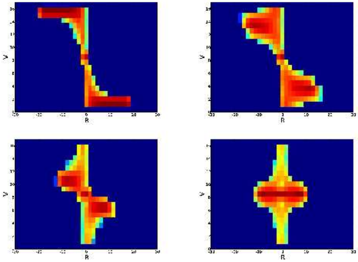
Position-velocity diagrams



Theoretical position-velocity diagrams

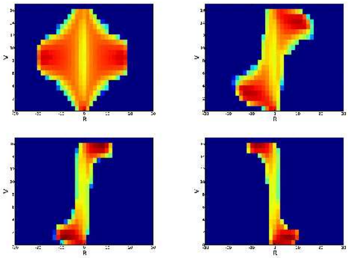
Rotating disk (flat v_r)

PA = 0, 30, 60, 90



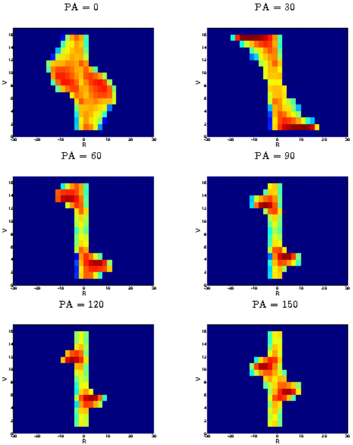
Expanding disk

PA = 0, 30, 60, 90

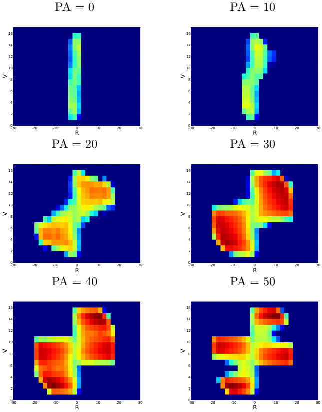


Theoretical position-velocity diagrams

Elliptical disk



Outflow in a hollow cone

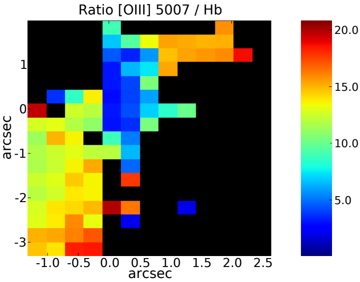


VIMOS – Q1505

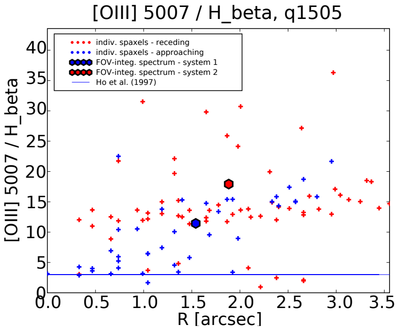
[O III]/Hβ

- [O III]/H$\beta > 3$, i. e. high excitation (AGN)

[O III]5007 /Hβ map



[O III]5007 /Hβ radial graph



Q1505 – Interpretation

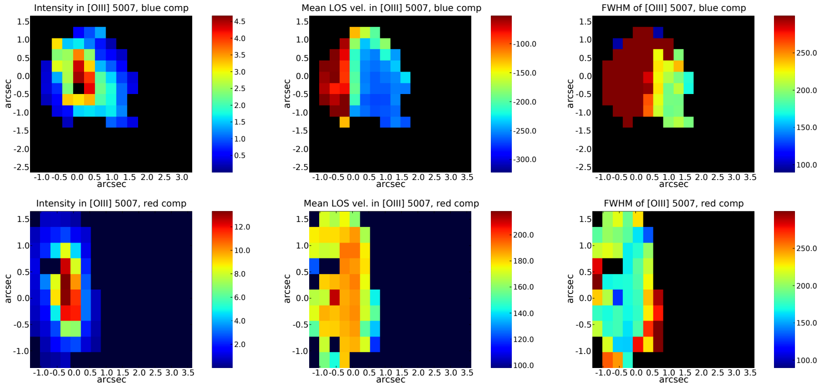
Elliptical ring ($r = 2.5$ kpc)?

- 2 emission-line regions (5 kpc sepation),
  – off-centered, but aligned with continuum
- High excitation ([O III]/Hβ)
- Simple narrow lines (200 km/s)
- FOV spectrum double-peaked
- Velocity map: rotation (?), maxima off-axis
- 1D rotation curve at PA = – 45 deg
- Velocity channel maps: do not have the “V-shapes” typical of rotation. Effect of resolution?
- P-V diagrams: rotation (?)
- FWHM different in the two parts of the ring

VIMOS – Other targets

Q1509

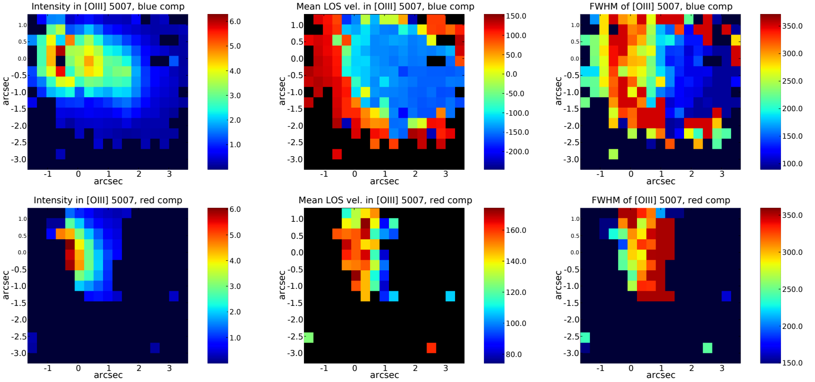
I [OIII] comp1 comp2 | v [OIII] comp1 comp2 | FWHM [OIII] comp1 comp2



VIMOS – Other targets

Q1418

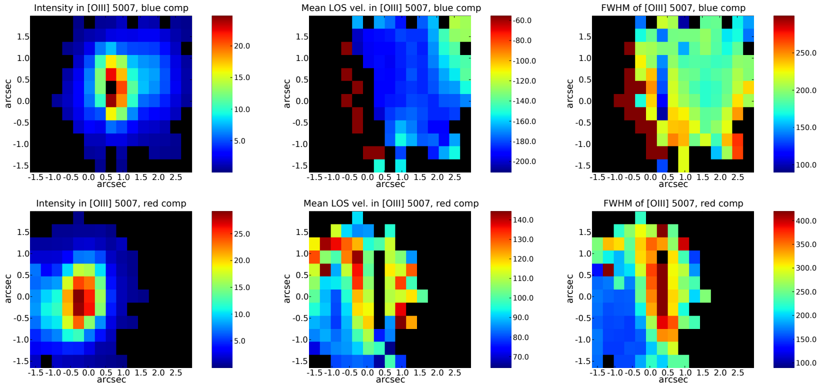
I [OIII] comp1 comp2 | v [OIII] comp1 comp2 | FWHM [OIII] comp1 comp2



VIMOS – Other targets

Q1616

I [OIII] comp1 comp2 | v [OIII] comp1 comp2 | FWHM [OIII] comp1 comp2



VIMOS – Summary of results

- No obvious binary sources in continuum emission
  $\rightarrow$ study in more detail
- [O III] emission 2 – 3 kpc, mostly aligned with continuum
- 2 kinematic components overlap in space
- Double-peaked [O III] 5007, Hβ in spatially resolved spectra
- Signs of rotation (?)
- [O III] / Hb ratio generally high

Further exploration of VIMOS data

- Explore the velocity space
  - more kinematic models, more realistic
  - include overlapping NLRs from 2 AGN
  - use all the possible mappings (I, v, FWHM, channel maps, p-v diagrams) to determine best-fitting model
  - Fourier decomposition (kinemetry, Krajnović et al. 2006)
- Combine gas emission data with stellar continuum
  - Look for disturbed morphologies indicating mergers
  - Absorption lines (e.g. Mg 5170) and the 4000 Å jump $\rightarrow$ derive stellar kinematics, population ages
- Search for other emission lines
  - e. g. [O III] 4363 Å $\rightarrow$ derive temperature

[O III]/Hβ ratios